Calculating the electromagnetic wave generated by the interaction between an ultrashort laser pulse and matter

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A self-consistent solution is obtained for the problem of electron flux generation by interaction between an ultrashort laser pulse and a metal target. © *1998 American Institute of Physics.* [S1063-7850(98)01603-6]

INTRODUCTION

The interaction between high-intensity ultrashort laser pulses and matter results in the generation of fast electrons with effective temperatures $T_f \approx 10$ keV and $T_f \approx 100$ keV for laser power densities on the target $q_l \approx 10^{16}$ W/cm^2 and $q_l \approx 10^{17}$–10^{18} W/cm^2, respectively.[1–3] The laser radiation is converted to fast electrons with an efficiency A_f of order tens of percent.[1]

On leaving the target, the fast electrons create electromagnetic fields which act so as to return them back to the generation zone. The motion of the electrons in the self-consistent electromagnetic fields beyond the target may lead to the dipole emission of an ultrashort, high-power electromagnetic wave. Since the emission region is small, the wave may subsequently be focused by the usual means for fundamental and applied research purposes. It is of interest to estimate the possible efficiency for conversion of the fast electron energy into an outgoing electromagnetc wave.

Here we present results of calculations made using the PM2D code to model the motion of the fast electrons and electromagnetic fields generated by the interaction of a picosecond laser pulse and a planar target at intensity $q_l \approx 10^{16}$ W/cm^2.

FORMULATION OF THE PROBLEM AND METHOD OF SOLUTION

Laser radiation focused in a beam of radius r_0 is incident normally on the surface of a metal plate. The time dependence of the supplied laser power $P(t)$ is described by an isosceles triangle with a base duration of 10^{-12} s and peak $P_{\max} = 10^{10}$ W. Near the spot a surface source of fast electrons is defined with an isotropic angular distribution and a Maxwellian energy spectrum with the temperature

$$T_e(t) = 100 \times \left(\frac{P(t)}{\pi r_0^2 q_0} \right)^{1/3}. \tag{1}$$

Here T_e is in keV, the laser radiation power $P(t)$ is in watts, and $q_0 = 10^{18}$ W/cm^2.

The fast electron flux leaving the plate is given by

$$F(t) = 6.3 \times 10^{29} \times \left(\frac{P_{\max}}{\pi r_0^2 q_0} \right) \times A_f \times \left(\frac{P(t)}{\pi r_0^2 q_0} \right)^{2/3}, \tag{2}$$

where $F(t)$ is measured in particles/(cm^2/s) LB. and A_f is the efficiency of conversion of the laser radiation energy into fast electron energy.

The motion of the fast electrons is described by

$$\frac{d\mathbf{p}}{dt} = e\left[\mathbf{E} + \frac{1}{c}(\mathbf{v} \times \mathbf{H}) \right], \quad \frac{d\mathbf{r}}{dt} = \mathbf{v}, \quad \mathbf{v} = \frac{c\mathbf{p}}{\sqrt{p^2 + m^2 c^2}}, \tag{3}$$

where m is the electron rest mass.

The Maxwell equations in a cylindrical coordinate system are used to determine the fields. The initial conditions are taken as zero. The boundary $z=0$ (surface of the plate) is assumed to be conducting ($E_r = 0$). The other boundaries $z = z_{\max}$ and $r = r_{\max}$ are also conducting, but they are some distance away and do not influence the field distribution inside the spot.

The calculation algorithm of our PM2D method is based on splitting into physical processes, which implies systematic modeling at each time step:

– the injection of fast electrons;
– motion of the electrons in electric and magnetic fields;
– the electron current distribution in the region;
– the electric and magnetic fields.

Making the time step small compared with the characteristic time of variation of the electric and magnetic fields ensures that the calculations of the electron motion and the fields are self-consistent.

The particle method is used to model the space–time distribution of the electrons. An explicit ''cross-shaped'' difference scheme is used to find the numerical solution of the Maxwell equations.

RESULTS AND ANALYSIS

Calculations made for the parameters $A_f = 10^{-1}$–10^{-3} and $r_0 = 20$–5 μm show that most of the electrons are trapped by the electric field in a region of characteristic size ~ 1 μm near their surface of generation. The highest-energy electrons escape from this region and then move back toward the surface of the target with a helical motion. Some of them reach this surface where they are absorbed.

As a result of the nonuniform (mainly along z) electron motion, an electromagnetic wave is generated. All the prerequisites of dipole radiation are present in our case, and the

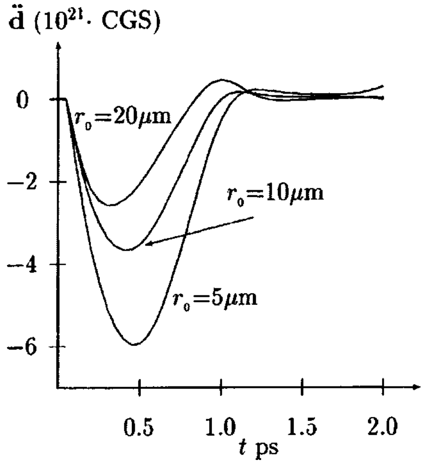

FIG. 1. Time dependence of the second derivative of the dipole moment for various radii of the laser radiation spot for $A_f = 0.01$.

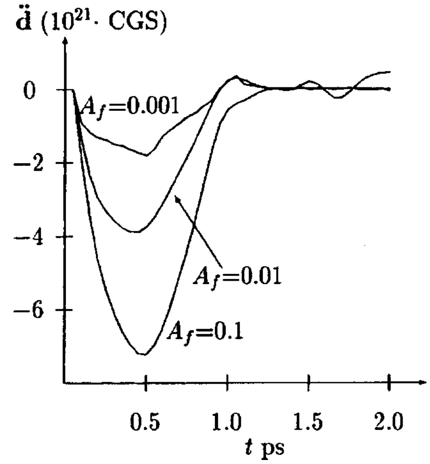

FIG. 2. Second derivative of the dipole moment assuming various laser energy conversion efficiencies for $r_0 = 10$ μm.

parameters of the outgoing electromagnetic wave can be determined by calculating the time dependence of the second derivative of the dipole moment with respect to time $\ddot{\mathbf{d}}$. The dipole radiation power is given by

$$I = \frac{2}{3c^3}\ddot{\mathbf{d}}^2, \quad \ddot{\mathbf{d}}^2\left(\frac{d}{dt}\int j_z dV\right)^2. \tag{4}$$

The fields **E** and **H** at the observation point at distance R are related to the dipole moment by the well-known relations[4]

$$\mathbf{H} = \frac{1}{c^2 R}\ddot{\mathbf{d}}\times\mathbf{n}, \quad \mathbf{E} = \frac{1}{c^2 R}[(\ddot{\mathbf{d}}\times\mathbf{n})\times\mathbf{n}]. \tag{5}$$

Here **n** is the unit vector directed from the center of the target to the observation point.

Figures 1 and 2 display the second derivative of the dipole moment of the fast electrons as a function of time for various values of the parameters r_0 and A_f. The calculations made using the PM2D program show that the efficiency of conversion of the laser radiation into an electromagnetic wave may reach $K_{\max} = I_{\max}/P_{\max} \approx 10^{-5}$ for $r_0 = 10$ μm and $A_f = 0.1$, and also for $r_0 = 5$ μm and $A_f = 0.01$, which corresponds to conversion of fast electron energy into electromagnetic pulse energy with efficiencies $\eta = K/A_f \approx 10^{-4}$–$10^{-3}$.

CONCLUSIONS

Calculations made using the PM2D program have shown that fast electron energy may be converted into subpicosecond electromagnetic pulses with an efficiency of 10^{-3}–10^{-4} when the intensity of the ultrashort laser radiation on the target is 10^{16}–10^{17} W/cm^2.

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